

PERMANENT MAGNET DESIGN METHODOLOGY

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ABSTRACT

Design techniques developed at ETDL for the exploitation of high energy magnetically rigid materials such as Sm-Co and Nd-Fe-B have resulted in a revolution in kind rather than in degree in the design of a variety of electron guidance structures for ballistic and aerospace applications. Some of the salient examples are:

- 1) magnets for traveling wave tubes that have from one to two orders of magnitude advantage in field-to-mass ratio over conventional structures.
- 2) permanent magnet solenoids for high-powered klystrons that generate thousands of gauss of field uniformly over cylindrical volumes that are a meter long and one half meter in diameter.
- 3) sources of transverse magnetic fields of several kilogauss and parts-per-million uniformity for use in magnetic resonance imagers (MRI) for medical diagnostics, airport baggage scanners and general lab use.
- 4) compact, light-weight, high-field, finely tunable free electron laser magnets that require no power supply and exhibit minimal stray fields.
- 5) two-tesla magnetic fields generated by grapefruit-sized structures in one inch spherical cavities for optical Faraday rotators and short path traveling wave tubes.

INTRODUCTION

A perennial barrier to the application of the latest high-powered radiation sources to airborne, ballistic, and the more highly mobile surface vehicles has been the excessive mass, bulk and dependence on power packs of the electron beam focussing magnets that such sources employ. Until relatively recently, attainment of magnetic fields of several thousand gauss over large gaps or volumes depended upon bulky electro-magnets with equally cumbersome power supplies or on large masses of conventional magnet materials whose weight and bulk severely limited application to mobile devices. Many field configurations were unattainable even with combinations of extraordinarily large mass, high current, and small volume.^{1,2}

With the advent of the magnetically rigid high energy product rare earth permanent magnet materials (REPM's), these difficulties became tractable and whole families of previously unattainable devices became viable. Such materials are characterized by very high remenance and coercivity. The former is a measure of a material's ability to provide large amounts of magnetic flux, while the latter is a measure of its rigidity, that is, ability to maintain magnetization in the face of strong opposing magnetic fields that arise from geometric demagnetization effects or from externally applied sources. Such fields are always present in permanent magnet devices, especially in the compact structures that are so important to the military.

Although the high energy product materials (Samarium-cobalt, neodymium-iron-boron, mischmetal, etc.) have been commercially available for almost two decades, they have not been exploited to the revolutionary extent warranted by their properties. This seems to be because force of custom causes designers to employ the new materials to improve performance of old structures rather than to use them in entirely new designs that are not practicable with the old materials. In this regard, the magnetics group at ETDL has been an exception in, that over the past decade, it has striven to formulate general design

principles needed to afford these principles to obtain efficient, compact, and lightweight devices viz radars, radios, electronic warfare, fuses, magnetic resonance imagers for medical diagnostics, motors, generators and others. This work has resulted in the disclosure of over one hundred patents and the construction of several prototype models of which some of the most advanced will be discussed in this paper. These structures fall roughly into four broad classes with some overlap.

Permanent Magnet Solenoids

Permanent magnet solenoids (PMS) provide uniform fields of thousands of oersteds over considerable lengths in cylindrical structures.^{3,4} Before the advent of REPM's, such fields were attainable only with electrical solenoids that were generally cumbersome, consumptive of electrical energy and dependent on electric current sources for their operation. The latter are not conveniently portable and do not lend themselves readily to providing field to small spaces with compact structures. In contrast, permanent magnet solenoids generate fields of up to slightly more than half of the remanances of the permanent magnets used (typically about 10kG for REPM's) in cylindrical spaces of arbitrary dimension without the drawbacks of electrical solenoids. The generated magnetic flux is essentially confined to the device and stray fields are minimal. This is accomplished by a configuration that maintains an equipotential everywhere on its outer surface. These configurations consist of three parts: an axially magnetized cylindrical shell which supplies the flux; iron discs that guide that flux into and out of the ends of the cylindrical cavity; and radially magnetized conical cladding which together with axially magnetized discs at the ends, and obliquely magnetized rings in the corners, confines the flux to the interior. Variations of the basic design can produce fields with gradients along the principal axis while maintaining field uniformity over any cross section.³ Other variations can confine flux to annular ring shaped regions.⁵ The PM's are useful in various electron beam devices such as traveling wave tubes, klystrons, cross-field amplifiers and gyrotrons.⁶ Representative structures are shown in Figures 1-6 in which magnetization vectors are represented by thin arrows and the working field vectors by thick arrows.

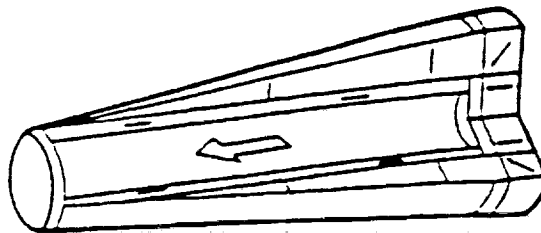


Figure 1. Single chambered Neugebauer structure. Left pole piece is taken as zero potential and outer surface everywhere is lowered to the same potential by inward-pointing cladding magnets. In this way, flux is confined to the interior.

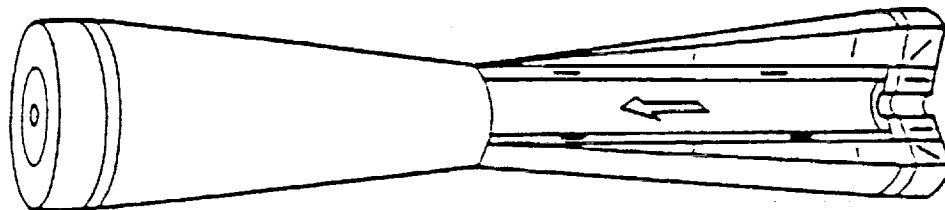


Figure 2. Because the zero potential reference has been moved to the middle from the end, the ETDL structure pictured here has less than half the mass of the Neugebauer design of Figure 1. Solenoidal fields up to 5 kOe are easily produced in this manner, in a structure much lighter than an equivalent electric solenoid and its power supply.

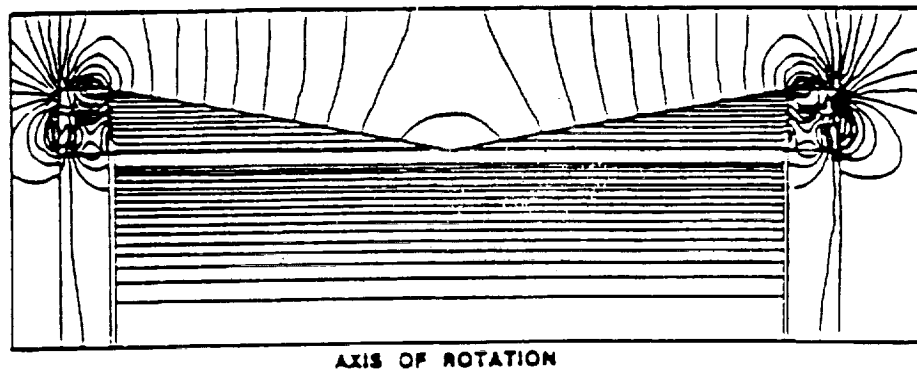
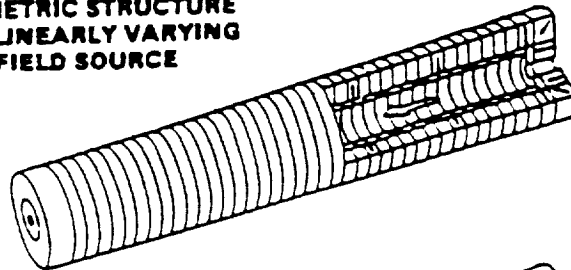


Figure 3. Flux plot of magnetic field produced by the permanent-magnet solenoid of Figure 2. Note the great uniformity over the working space. Apparent flux crowding towards the periphery is because each line represents a unit of flux in an annular ring of given thickness. Actual leakage is only a few percent and is due to imperfect cladding at the corners.

**PARAMETRIC STRUCTURE
FOR A LINEARLY VARYING
AXIAL FIELD SOURCE**



**GEOMETRIC STRUCTURE FOR
A LINEARLY VARYING AXIAL
FIELD SOURCE**

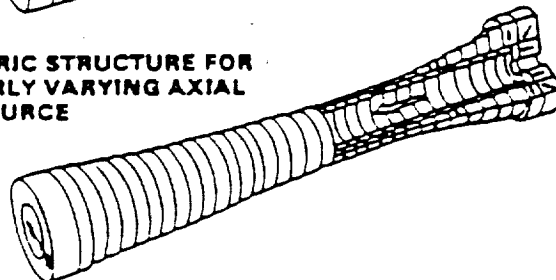


Figure 4. The ETDL permanent-magnet solenoid can be modified to produce fields that vary along the axis. Both of the pictured structures accomplish this. The parametric version controls the variation by modulation of the magnetic properties. In the geometric version, structural dimensions are modulated.

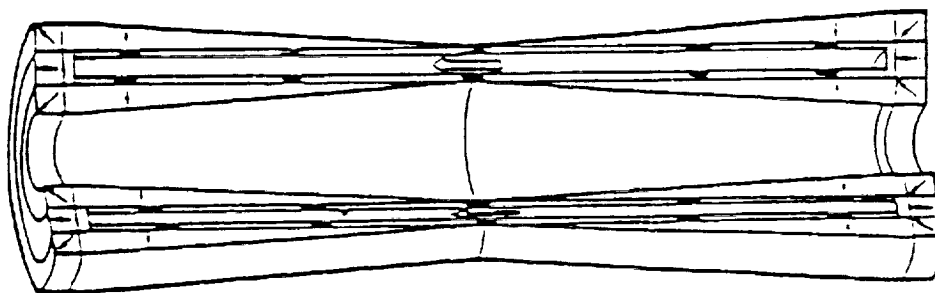


Figure 5. The field in the annular working space is supplied by the axially oriented magnetic shells. The radially oriented shells and end magnets confine the flux. Applications include hollow beam devices.

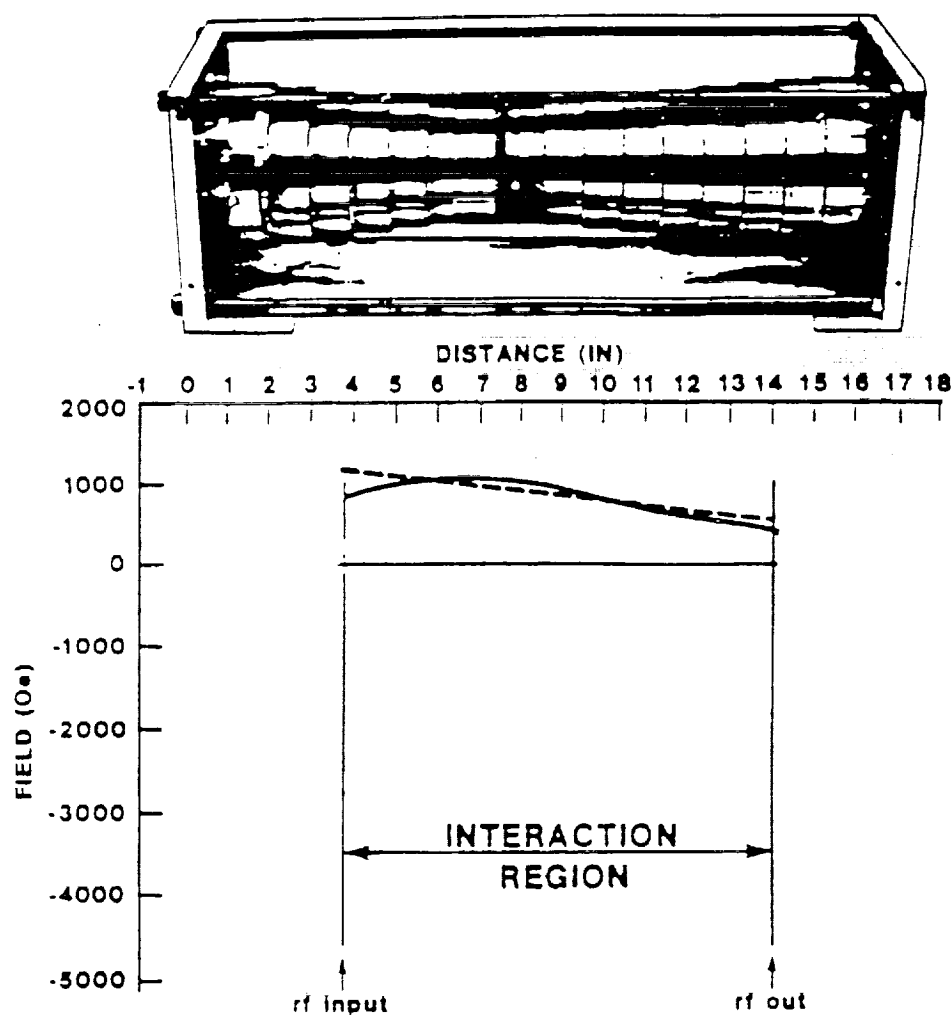


Figure 6. Axially tapered field solenoid.

Figure 6 shows an axially tapered field solenoid that was constructed for an advanced prototype of a mm wave source invented at ETDL. This device requires a solenoidal field that tapers from approximately 1000 oersteds, where the electron beam enters the interaction chamber, to 500 oersteds at the collector end of the chamber. Also, shown is a comparison of the measured field dependence on axial distance with the calculated dependence. While the compromises and approximations made in construction (e.g., substitution of steps for a continuous taper in the outer magnet) result in some deviation from the desired field, agreement is sufficiently good for operation of the tube. The permanent magnet weighs forty pounds and is to replace an electric solenoid which, together with its power supply, weighs over six hundred pounds. the solenoid is also tied to a current source and consumes considerable electrical energy. Furthermore, its stray magnetic field is strong at a considerable distance from the structure; while for the permanent magnet source, the field is largely confined and therefore affords closer packing of field sensitive instrumentation in its vicinity. The permanent magnet structure clearly affords an enormous enhancement in mobility, efficiency, convenience and tractability so that devices formerly confined to fixed stations, ships and large surface vehicles can now be employed in airborne, ballistic and highly mobile surface devices. Permanent magnet solenoids in various stages of design at ETDL include:

- a) A field source for an advanced, compact, high-power gyro-amplifier for near-mm waves, designed by ETDL at the request of a major manufacturer.
- b) A source for a bi-chambered gyrotron.⁷ This source produces a field of 2000 oersteds in the larger chamber and 500 oersteds in the smaller. Through techniques developed at ETDL, this can be accomplished in an abrupt step in field at the juncture of the two chambers.
- c) A field source for an extended interaction amplifier to replace a cumbersome, power-consuming electromagnet was designed at the request of another manufacturer.
- d) A permanent magnet source to lighten cross-field and extended interaction amplifiers.
- e) A klystron magnet for a microwave source for a free electron laser amplifier.
- f) A field source for a satellite-borne X-Ray/UV Telescope for NASA.

None of these structures would be viable with conventional magnet materials. This is illustrated in Figure 7. Permanent magnet solenoids all contain magnets operating at point B=0, $H = B H_C$ where $B H_C$ is the coercivity. Since the mass and volume of a permanent magnet solenoid are roughly inversely proportional to the square of its coercivity, it is clear that use of Alnico or similar materials would result in a prohibitively bulky structure, two orders of magnitude heavier and larger than Sm-Co magnets producing the same field.

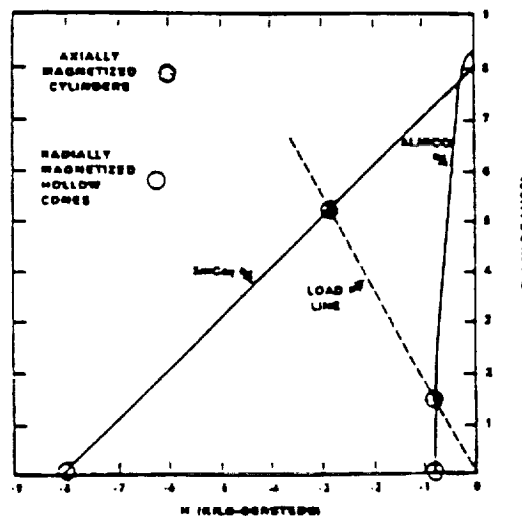


Figure 7. Operating points for permanent magnet solenoid.

Transverse Field Sources

Cylindrical structures that produce fields in interior cavities transverse to their axes are illustrated in Figures 8-13. As in the permanent magnet solenoids, the flux in these structures is confined to their interiors.^{3,9-12} The structures in Figures 9-13 also confine flux to their interiors, but employ no iron pole pieces which help "smooth out" small field distortions engendered by structural defects incurred in the course of manufacture and assembly. They can, however, provide much larger fields than structures with iron poles and are limited in field only by the practical considerations of allowable bulk and weight. Figure 13 shows an adjustable version of Figure 12. Field variation is effected by dividing the basic cylinder into two nested rings, each of which contributes the same field to the interior. When the rings are rotated by the same angle in opposite directions, their vector sum will be in the same direction as the original field but smaller. In this way, any field in the range $\pm B_{\max}$ can be supplied to the interior without the use of electric currents. All the

configurations of Figures 8-13 have potential use in magnetic resonance imaging, or in any application in which uniform transverse fields of thousands of gauss are needed. They are of special value in medical diagnostics because of their small bulk relative to superconducting magnets and their freedom from power sources, cryogens and energy expenditure.

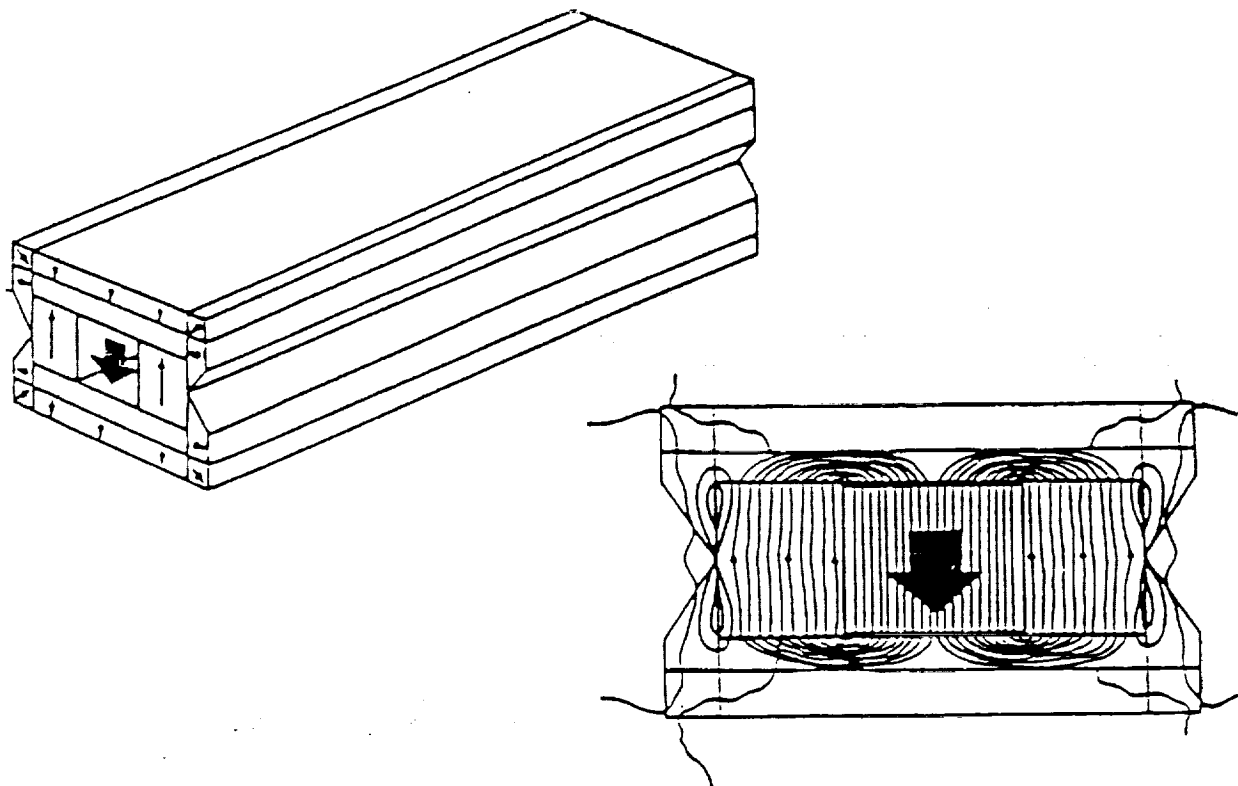


Figure 8. Structure with uniform transverse field in a rectangular working space. The large arrow shows the working field direction and the small arrows show magnet orientations. Possible uses are in NMR imagers and bases for twister structures. Note the field uniformity in the computer flux plot of the cross section.

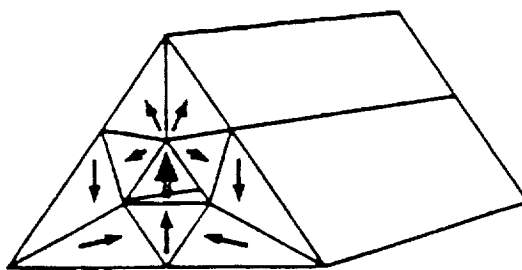


Figure 9. This structure produces a field of one-half the remanance in a triangular cavity. By successive nesting of many of these structures, arbitrarily high fields are attainable.

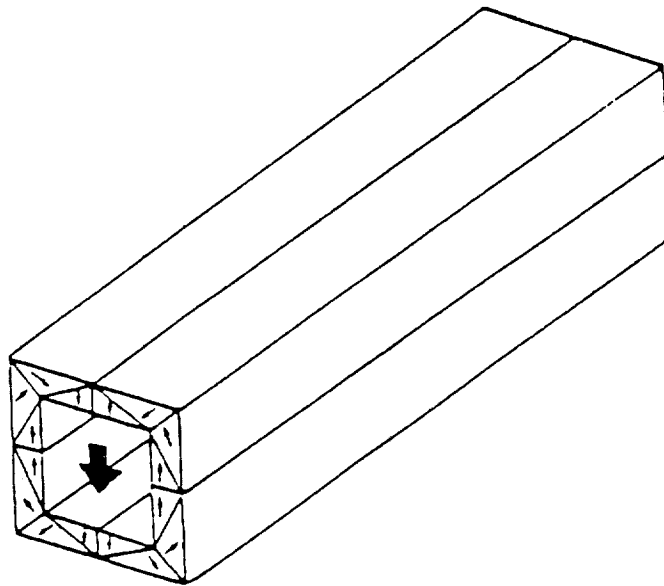


Figure 10. Square permanent magnet structure. As with the rest of the structures on this page, flux is confined to the interior and field augmentation can be attained by sequential nesting.

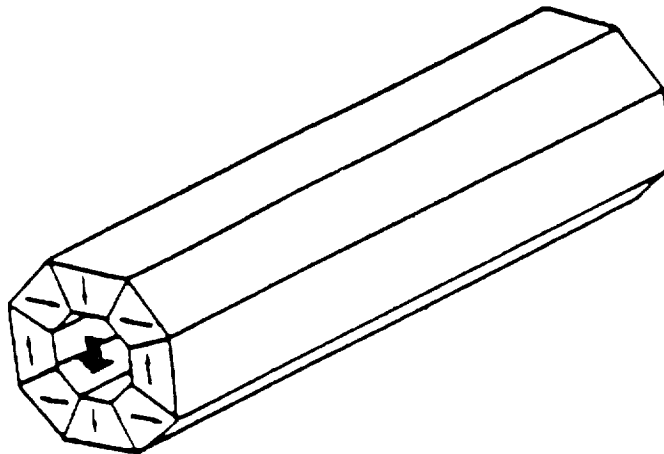


Figure 11. Octagonal dipole structure. Fields attained in these structures are 90 percent of those of the ideal circular structure of Figure 12.

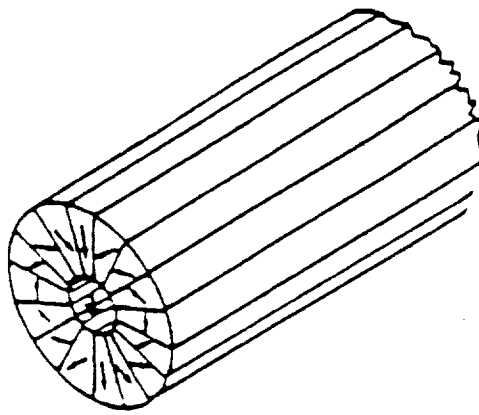


Figure 12. The magnetic orientation (small arrows) varies continuously as 2θ . A dipolar field (large arrow) is thereby produced in the interior cylindrical cavity of magnitude $H = B_r \ln(P_o/P_i)$. P_o and P_i are the outer and inner radius of the annular magnet.

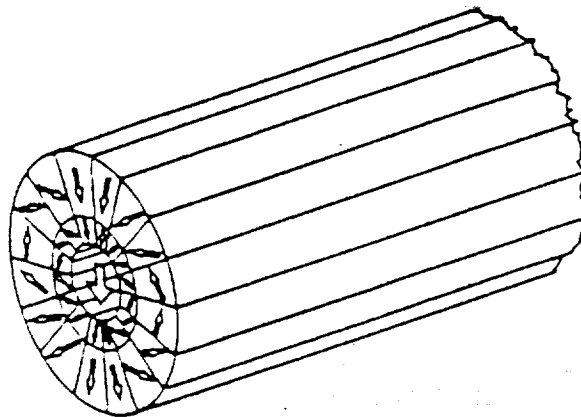


Figure 13. The inner and outer cylindrical shells of the above structure produce the same field H_o in the cavity. Therefore, rotation of the rings with respect to each other yields any field between $\pm 2H_o$ in the cavity.

At present, these drawbacks limit MRI's to large, wealthy institutions where an entire suite can be dedicated to their use. The structures that employ permanent magnets can be made much more cheaply and afford a degree of portability not attainable with superconducting magnets. Therefore, military field use down to divisional or even brigade level is not inconceivable. Moreover, the permanent magnet structures lend themselves readily to miniaturization so that much smaller and more mobile systems could be made for the examination of human extremities and heads. The same miniature systems could also serve as pedagogical devices for the quick training of large numbers of MRI technicians. Applications to anti-terrorist and anti-drug activities also seem feasible; most notably for baggage inspection for contraband at airports and harbors. Several small MRI magnets have already been built and one of half-body size is in the process of assembly and adjustment.

Periodic Structures

A third set of magnetic configurations is formed from cross sectional slices of the second set arranged in periodic arrays as in free electron lasers (FEL) such as wigglers and twistors (Figures 13, 14 and 15). Such FEL arrays produce higher fields than conventional configurations of similar period, beam diameter and structural mass. They can also be corrected for small field distortions arising from dipoles that must be placed in the inner corners of the polygonal structure to effect the desired compensation. The procedure is particularly valuable in FEL's which are notoriously difficult to adjust. Adjustment is further facilitated by use of the bi-ringed nested structure mentioned above.

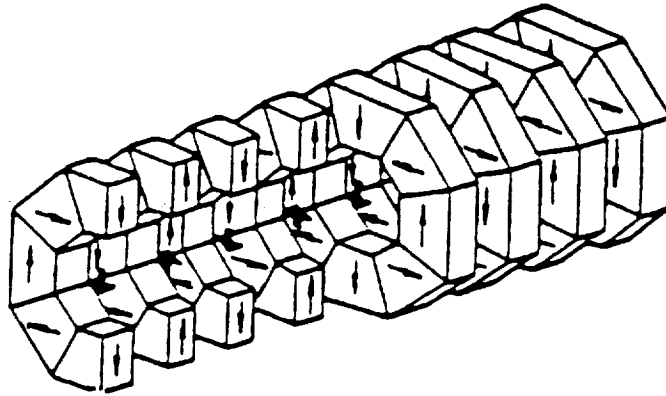


Figure 14. Wiggler structure composed of sectional slices of configuration 11.

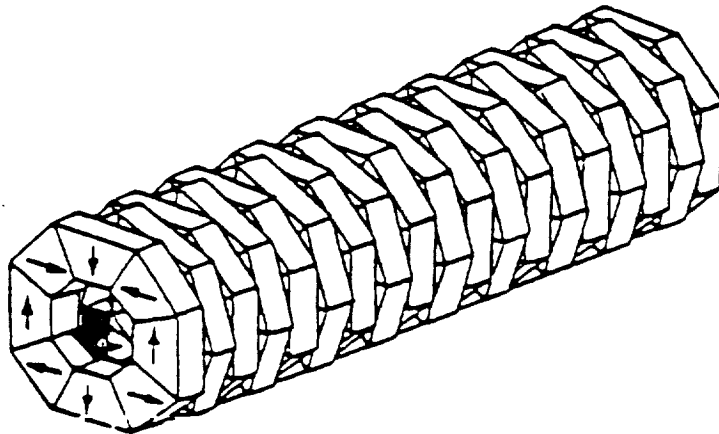


Figure 15. Twister structure composed of sectional slices from the configuration of Figure 11.

In FEL's, an electron beam is sent through a transverse magnetic field that changes directions in a periodic fashion. If the field alternation is roughly sinusoidal as in Figure 14, the electron beam is accelerated from side to side in a direction normal to both its translational motion and the applied field and hence, the device is called a wiggler. The acceleration caused the electrons to radiate energy at the frequency determined by electron velocity and wiggler period. If the proper relationship between velocity, field strength and period exists, the radiation from all parts of the wiggler reinforces and a type of laser action results. When such a relationship exists, the wiggler is called an undulator. If the field remains constant in magnitude but rotates continuously along the structural axis, the electrons are made to follow helical rather than sinusoidal paths and the emitted radiation exhibits circular rather than plane polarization. Such a structure is called a twister or helical free electron laser. Circularly polarized radiation gives radars certain enhanced discriminatory properties compared to plane polarized radiation and is therefore preferable for certain military applications. At the request of the Naval Research Laboratory, a simple permanent magnet twister structure was designed at ETDL that replaces a ponderous electromagnetic field source and its power supply with the usual advantages as is illustrated in Figure 16. A prototype was constructed and found to produce the calculated field of 1200 oersteds as compared with the 500 oersteds delivered by the present coil with the dissipation of 200 amps of electricity.

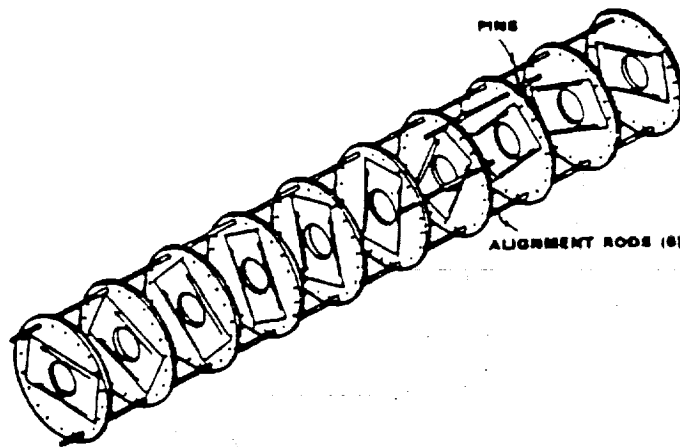


Figure 16. Exploded view of twister structure.

Traveling wave tubes are an important source of mm and microwave radiation for radars and radios. In such tubes, the electron beam is guided by a periodic axial field. Such fields are usually provided by an array of toroidal magnets whose magnetizations are axially oriented in alternate directions and which are interspersed with iron pole pieces that lead magnetic flux into the working space (see Figure 17a). Since such structures are often used in airborne and ballistic devices, where weight and bulk are critical, it is of paramount importance to keep them as light and compact as possible. This is especially true for miniature remotely piloted airborne vehicles where every pound of weight saved can translate into a considerable increase in range or effective payload.

Structures 17b, 17c and 17d were designed and constructed by ETDL to fulfill this need for lighter TWT structures.^{14,15} The configuration of 17b produces the same field as that of 17a with one half as much material while those of 17c and 17d result in from one to two order-of-magnitude mass reductions. The latter two arrays, however, are more difficult to manufacture and adjust and so are not so desirable as 17b except in applications with the most stringent of mass limitations. Structure 17c and 17d are very similar with regard to field to mass ratio and differ mainly in that the focusing ability of 17d is enhanced by a stronger field gradient that exists between its axis and the inner walls of the tube. Both tubes exhibit much better flux confinement than does the conventional structure 17a.

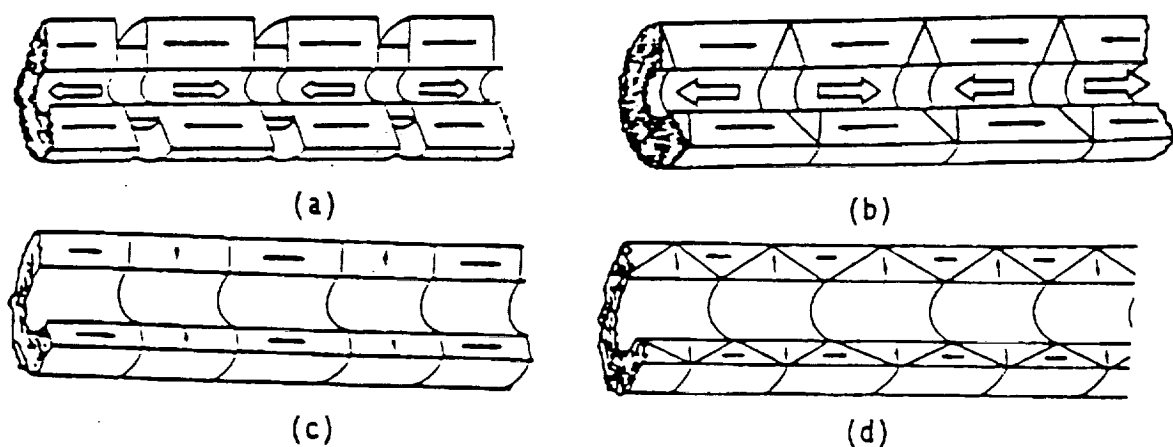


Figure 17. A) Conventional periodic permanent magnet stack for traveling wave tubes. Iron rings are sandwiched between the axial magnetic guide flux into the bore. B) A stack with triangular pole pieces. C) An all permanent-magnet stack consisting of both radially and axially magnetized rings producing the same field as (A) with 1/20th the mass and bulk for a field amplitude of 5.0 kOe. D) A stack with similar performance to that of (C) but with a larger field gradient in the bore.

Very High Field Structures

The fourth class of novel structures is generated by rotations of laminar sections of the second class about their polar axes. Figures 9-12 depict representative examples. Such structures produce, in their interior cavities, the very highest fields presently obtainable with permanent magnet structures. For example, in a spherical structure with an inner diameter of one inch, a field of two tesla is obtainable with an outer diameter of 4.5 inches if a remanence of 10 kG is used. With a Nd-Fe-B magnet of 12 kG remanence, the same field is obtainable with an outer diameter of only 3.5 inches.

If a structure of this type is cut in half at the equator and placed on a planar passive ferromagnet such as iron or permendur, the anti-mirror image formed in the ferromagnetic plane produces the same field as the missing half of the original sphere. Such a system is easier to manufacture as it requires only half as many pieces. It also provides more convenient access to the interior as no holes need be bored through the expensive permanent material and different access configurations are easily obtainable in the same hemisphere with different iron plates thereby adding greatly to versatility of use (see Figure 18).

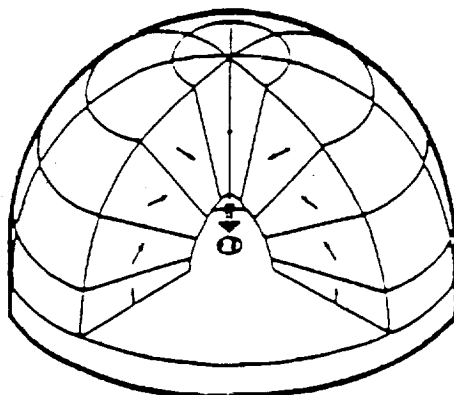


Figure 18. "Magic Igloo," hemispherical magnet set on iron plate.

These structures are useful where very high fields are required such as in some Faraday rotators and short travel beam tubes. Such structures placed in tandem may also be useful as wiggler elements when placed with poles normal to the electron-beam axis or as traveling wave tube elements when arranged in tandem, parallel to the beam axis.

REFERENCES

1. H. A. Leupold, E. Potenziani II, and J. P. Clarke, Proc. Ninth International Workshop on Rare-Earth Magnets, Bad Soden, West Germany, p. 109, (1987). Available from Dr. K. Strnat, E. E. Dept. of University of Dayton, Dayton, OH.
2. H. A. Leupold, E. Potenziani II, J. P. Clarke, and D. Basarab, Materials Research Society, Symp. Proc. 96, p. 279 (1987).
3. J. J. Clarke and H. A. Leupold, IEEE-Mag, Trans. of the Magnetics Society, Mag-22, No. 5, p. 1066.
4. H. A. Leupold and E. Potenziani II, IEEE-Mag, Trans. of the Magnetics Society, Mag-22, No. 5, p. 1078 (1986).
5. J. J. Clarke, E. Potenziani II, and H. A. Leupold, Jour. of Applied Physics 61, (8), p. 3468 (1987).
6. H. A. Leupold, "Powder Metallurgy in Aerospace and Defense Technologies," p. 167 (1990).
7. H. A. Leupold, E. Potenziani II, and A. Tilak, Jour. of Applied Physics 67, p. 4650 (1990).
8. J. Lowrance, C. R. Joseph, H. A. Leupold, and E. Potenziani II, to be published in "Advances in Electronics and Electron Physics" (1991).
9. M. G. Abele and H. A. Leupold, Jour. of Applied Physics 64, p. 5988 (1988).
10. H. A. Leupold, E. Potenziani II, and M. G. Abele, Jour. of Applied Physics 64, No. 10, p. 5994 (1988).
11. M. G. Abele, 10th International Workshop on Rare-Earth Magnets and Their Applications, Kyoto, Japan, 16-19 May 1989 (Proceedings Book: The Society of Non-Traditional Technology, 1-2-8 Toranomou Minato-ku, Tokyo, 105 (Japan).
12. K. Halbach, Proc. of the Eighth International Workshop on Rare-Earth Magnets and Their Applications, Dayton, OH, p. 123 (1985).
13. A. B. C. Marcos, H. A. Leupold, and E. Potenziani II, IEEE-Mag. Trans. of the Magnetics Society, Mag-22, No. 5, p. 1066 (1988).
14. H. A. Leupold and E. Potenziani II, Jour. of Applied Physics 67, p. 4650 (1990).
15. H. A. Leupold, E. Potenziani II, and A. Tilak, to be published in Proc. of IEDM (1991).